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Testing of a One-Bladed 30-Meter-Diameter Rotor on the DOE/NASA Mod-O Wind Turbine

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U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind/Ocean Technology Division

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SUMMARY

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As part of the Federal Wind Energy Program of the Department of Energy, NASA Lewis Research Center conducted tests on the DOE/NASA Mod-0 horizontal-axis wind turbine with a one-bladed rotor configuration. The single blade had an overall length of 15.2 m, and used a pitchable tip that spanned 12 percent of the blade radius. The blade was balanced by a counterweight assembly that consisted of a solid steel ellipsoid supported at an outer radius of 4.6 m by a steel spar. The blade and counterweight assembly were mounted to a teetered hub in a downwind configuration.

The objectives of these tests were to obtain data on the performance, loads, and dynamic characteristics of an intermediate-size, one-bladed rotor. These data, measured at a nominal rotor speed of 49 rpm, were compared with corresponding data for a two-bladed rotor at 33 rpm, having the same blade length and airfoil characteristics. The two-bladed rotor was previously operated on the same machine. The one-bladed and two-bladed rotors used common components wherever possible and did not represent optimized rotor designs.

The results of the one-bladed rotor tests showed that this configuration can be operated successfully. There were no significant dynamic loads with this configuration, and the fatigue loads were comparable to those of a two-bladed rotor. A decrease in power output equivalent to a reduction in wind-speed by 1 m/sec occurred with the one-bladed rotor when compared with the aerodynamically similar two-bladed rotor operating at two-thirds of the rotor speed. Analytical methods for predicting the performance and dynamic characteristics of a one-bladed rotor were verified.

INTRODUCTION

The concept of a one-bladed, horizontal-axis wind turbine has been of interest to wind turbine designers for many years (ref. 1). This interest has been spurred by analyses that have indicated several economic advantages of the one-bladed rotor over multibladed rotors. These advantages include the obvious elimination of one or more blades, lower drivetrain torque for a given power output (because of higher rotor speed), and simplified control mechanisms. In addition, rotor hub design and construction could be simplified, and the blade could have less stringent aerodynamic shape tolerances.

The above advantages need to be balanced against the concerns raised by using a one-bladed rotor design. These concerns include the possible dynamic problems inherent in an asymmetric rotor, as well as a more variable output torque. In addition, the anticipated decrease in power output of a one-bladed rotor configuration needs to be considered in cost trade-off studies.

Although most investigators believe that the economic advantages of a one-bladed rotor outweigh the technical difficulties involved, experimental data are obviously needed. Comparative tests are needed in which only the number of blades is changed. Such tests would quantify differences in performance and vibratory loads. The DOE/NASA Mod-0 200-kW wind turbine, with its available two-bladed data base, was used to test a one-bladed configuration that would require minimal hardware changes.

This report is an extension of the preliminary research documented in reference 2. Reference 2 contains analytical predictions of rotor performance, rotor power coefficient, teeter-angle behavior, and blade flapwise bending moments for the one-bladed rotor. This report documents the results of the tests conducted on the one-bladed rotor configuration, and compares these measured results with those of a two-bladed rotor on the same Mod-0 machine.

TEST PROCEDURE

Turbine Configuration

The one-bladed rotor tests were conducted on the DOE/NASA Mod-0 200-kW wind turbine test bed located near Sandusky, Ohio. The testing period extended from September through November 1985. The wind turbine configuration tested (fig. 1) used a downwind rotor. The rotor centerline height was 38 m, with the nacelle mounted on a tubular steel tower. The tower is supported by a spring base which can be adjusted to vary the stiffnesses of the tower assembly, and therefore, the natural frequencies of the system.

The planform of the blade and counterweight assembly, which were mounted to a teetered hub, is shown in figure 2. The blade had a pitchable tip which spanned 12 percent of the blade radius. The tip could be deflected over a range from 0° to -90° , the angle at which the leading edge points into the wind. The inner-blade section was 11.2 m long, had zero twist, and was mounted with a pitch angle of 0° relative to the plane of rotation. A transition section, which housed the hydraulic pitch-change mechanism, was mounted to the end of the inner-blade section. The inner-blade section was constructed of a wood/epoxy composite, and the transition and tip sections were constructed with steel and plywood ribs attached to a tapered steel spar. A fiberglass skin over a foam-filled interior was used for the tip section, and the transition section was covered with sheet metal. The entire blade beyond the truncated region of the inner section had a NACA 23024 airfoil cross section.

The steel spars in the transition and tip sections, together with the pitch-change assembly, resulted in a relatively heavy outer blade. The total blade mass was 2200 kg, including a 182 kg spool-piece adapter mounted on the inner end of the inner-blade section. The first cantilever flatwise (out-of-plane) bending frequency was 2.8 Hz (nonrotating), and the first cantilever chordwise (in-plane) bending frequency was 3.4 Hz.

The counterweight, a solid steel ellipsoid weighing 2287 kg, was mounted to a steel spar attached to a spool-piece adapter. The entire counterweight assembly weighed 3690 kg. The outer radius of the assembly was 4.6 m.

When mounted to the teetered hub, the counterweight had 0° coning, and the blade had 3° downwind coning, at a teeter angle of 0°. The teetered hub was fitted with rubber stops to provide resistance to teeter motion. A static (nonrotating) teeter stiffness test established the relation between teeter angle and teeter axis moment (fig. 3). Note the hysteresis exhibited by the teeter stops.

The interior of the Mod-0 nacelle is shown in figure 4. The drivetrain includes a 45:1 parallel-shaft speed increaser with a disk brake on the high-speed output shaft. Multiple V-belts on the high-speed shaft drive a high-slip, wound rotor induction generator which is rated at 200 kW. The diameters of the V-belt pulleys can be changed to provide a variety of rotor operating speeds.

The yaw drive system consists of a single hydraulic yaw motor driving a pinion mated to the yaw gear attached to the nacelle. Throughout the one-bladed rotor tests, the desired yaw angle was maintained by operating the yaw system manually. The yaw brake is a large, hydraulically actuated disk brake that can be set to provide a range of braking torques.

The one-bladed rotor was tested at nominal speeds of 33 and 49 rpm. The 33-rpm tests were used as checkout tests to verify stable rotor dynamic operation. The majority of the tests were planned for operation at 49 rpm because this speed provides higher power output.

The spring base of the pole tower allows for tuning of the tower bending frequency. By increasing the compliance of the spring base, the first tower bending frequency was reduced from a previous value of 0.78 Hz (47 rpm) for the two-bladed rotor tests at 33 rpm to 0.60 Hz (36 rpm) for the one-bladed rotor tests. This allowed the wind turbine to operate successfully at 49 rpm after the rotor was accelerated through the resonant point during startup.

Data System

Rotor performance is based on measured generator power and reference windspeed. The reference windspeed is measured from one of five hub-height anemometers located 59 m from the wind turbine and in the directions of the predominant winds at the test site. During a test, the anemometer most nearly upwind of the turbine is selected to measure the reference windspeed. Blade loads are measured with strain gages mounted on the spool-piece adapters, 0.8 m (5.3 percent span) from the rotational axis. Yaw torques are measured at the output of the hydraulic yaw motor on the shaft of the pinion gear that drives the yaw gear. Rotor torque is measured by strain gages mounted on the low-speed shaft.

The data acquisition system collects and records maximum and minimum values from each sensor for each rotor revolution. Mean and cyclic values are then calculated from this recorded data. Mean values are calculated as

1/2(maximum + minimum) and cyclic values as 1/2(maximum - minimum). Additional data processing depends on the application.

The relation between rotor power and generator power was determined by calculating rotor power based on measured rotor drivetrain torque and speed. This empirical relationship, described in the following equation, was used to convert measured alternator power to rotor power for operation at 49 rpm:

$$P = 9.3 + 1.09 P_a + 0.00134 P_a^2 \quad (1)$$

in which

P rotor power, kW
 P_a alternator power, kW

Atmospheric pressure and temperature were taken for each test run, and the power was corrected to sea-level standard conditions. Because test runs were normally 4 hr or less in length, atmospheric conditions changed very little during a run. Consequently, a single calculation of air density sufficed for a given set of data. Rotor power was corrected to sea-level standard conditions in accordance with the following equation:

$$P' = \frac{0.05785 PT}{p} \quad (2)$$

where

P' rotor power at standard sea-level conditions, kW
 T air temperature during test run, °R
 p barometric pressure during test run, in. Hg

The effect of yaw angle variations on power output was taken into account by adjusting the rotor power to a zero yaw angle through use of the following equation:

$$P'' = \frac{P'}{3 \cos \psi} \quad (3)$$

in which

P'' rotor power at zero yaw angle, kW
 ψ yaw angle, deg

Combining equations (1) to (3) and deleting the prime notations yield

$$P = \frac{T}{p \cos^3 \psi} (0.538 + 0.063 P_a + 0.000078 P_a^2) \quad (4)$$

Thus, equation (4) was used to convert measured alternator power to rotor power for standard sea-level conditions at a yaw angle of 0°.

The necessary data processing to establish the rotor power with respect to the windspeed performance curve consisted of

- (1) Sorting to eliminate data points with yaw angles exceeding $\pm 15^\circ$.
- (2) Calculation of 1-min averages for generator power, reference wind-speed, and yaw angle.
- (3) Conversion of data points from mean per-revolution generator power to rotor power.
- (4) Sorting 1-min average points into windspeed bins and calculating the median value within each bin.

RESULTS AND DISCUSSION

The predicted and measured rotor power in relation to windspeed for both one-bladed rotor operation at 49 rpm and two-bladed rotor operation at 33 rpm are shown in figure 5. There is excellent agreement between the predicted and measured values of rotor power for the two-bladed rotor. The difference between predicted and measured values of rotor power for the one-bladed rotor increases with windspeed. Further investigation would be required to determine if the discrepancy is due to (1) limitations of the prediction code and the assumptions that are part of its theoretical basis, or (2) inadequacy of the treatment in the prediction method to account for three-dimensional flow effects such as rotor stall and blade-tip losses.

The measured power output for the one-bladed rotor is 15 to 20 kW below that of the two-bladed rotor for the windspeed range of 4.5 to 8 m/sec. A performance comparison can also be made by relating the windspeeds required for a given power output. Figure 5 shows that, to produce equivalent power, the one-bladed rotor requires a windspeed approximately 1 m/sec higher than that required by the two-bladed rotor.

The power loss results primarily from (1) aerodynamic drag on the counterweight assembly, and (2) increased blade-tip losses because of the higher speed of the one-bladed rotor. The power loss due to the counterweight assembly drag was estimated to be 9 kW (ref. 1). This loss could be reduced with aerodynamic fairing of the assembly. The tip losses could probably be reduced by optimizing the rotor design for one-bladed operation.

Cyclic power was not markedly different between the one-bladed and two-bladed rotors. It is possible that the high slip of the induction generator alleviated the effects of the higher cyclic torque from the one-bladed rotor. Slip is a characteristic of the generator and indicates a speed difference between the generator rotor and the line-synchronous speed of the rotating magnetic field. High slip results in a "soft" coupling between the wind turbine mechanical output and the utility grid.

Both predicted and measured cyclic flatwise blade-bending moments at 5.3 percent span are shown in figure 6 for the one-bladed and two-bladed rotors. To calibrate the dynamic load prediction code for the one-bladed rotor, the measured loads for the two-bladed rotor were used (ref. 2). The two-bladed rotor was operated in a power control mode that limited alternator power to 100 kW by pitching the blade tips. The power setpoint was reached at 9.5 m/sec. The one-bladed rotor had a power setpoint of 200 kW (electrical).

The tips did not pitch for the windspeed range shown in figure 6. Note that the cyclic flatwise loads are comparable for the two rotors.

The measured cyclic chordwise blade-bending moments at 5.3 percent span are shown in figure 7. The loads for the one-bladed rotor are almost independent of windspeed, and reflect the loading due to gravity. Also shown are loads data for a two-bladed rotor, which are again comparable. There is a slight increase in load with windspeed for the two-bladed rotor. This is probably due to the effect of blade-tip pitching to maintain the power setpoint.

Teeter angles for the one-bladed rotor are shown in figure 8. This figure shows mean teeter angle as a function of alternator power output for data sorted into three yaw-angle ranges. Mean teeter angle was plotted against alternator power because alternator power gives a good indication of the windspeed averaged over the area swept by the rotor. The mean teeter angles experienced by the one-bladed rotor become more negative as the power (windspeed) increases. A negative mean teeter angle is equivalent to an increase in the downwind coning of the blade above its initial value of 3° . Mean teeter angles were found to be affected by yaw error only when the magnitude of the error exceeded 25° to 35° .

Cyclic teeter angles for one typical test run are shown in table I. Median teeter angles are shown for data that were sorted into bins based on alternator power and yaw angle. Cyclic teeter angles are seen to be dependent on both windspeed and yaw angle, with a tendency toward lower teeter angles at moderate negative yaw angles.

The teeter motion of the one-bladed rotor was considered to be well behaved. The high teeter stability was attributed to the rubber teeter stops which provided nonlinear resistance to teeter motion. In addition to increasing stability at operating speeds, the teeter stops make possible rotor startup and shutdown without excessive teeter angles. Excessive teetering can be caused by the rotor center of gravity being overhung from the teeter axis and a lack of blade aerodynamic damping (due to low rotor speed). This could lead to high impact loads if the teetering rotor is allowed to contact the metal teeter stops.

CONCLUSIONS

The results of the test indicate that the concept of a one-bladed rotor is valid, at least for intermediate-size machines. There are, in fact, no significant dynamic problems with the configuration, and fatigue loads are comparable to those of a two-bladed rotor. A power output penalty equivalent to a 1-m/sec windspeed reduction occurs with the one-bladed rotor when compared with an aerodynamically similar two-bladed rotor.

The results and trends displayed in the one-bladed rotor tests are in general agreement with the analytical predictions presented in reference 2. More detailed and accurate analyses can be made by fine-tuning the input to match experimentally determined rotor characteristics such as blade natural frequencies and teeter stiffness.

These analytical tools can also be used to obtain an improved wind turbine design that is optimized for one-bladed operation. In particular, the

performance analyses could be used to define rotor design characteristics that would lead to improved performance.

REFERENCES

1. Pruyn, R.R.; Wiesner, W.; and Sulzer, P.G.: Performance and Structural Design Aspects of a One-Bladed Electric Power Generating Windmill. American Helicopter Society, 31st Annual National Forum Proceedings, 1985.
2. Corrigan, R.D.; and Ensworth, C.B.F.: Design and Initial Testing of a One-Bladed 30-Meter-Diameter Rotor on the NASA/DOE Mod-0 Wind Turbine. NASA TM-88810, DOE/NASA-20320/70, 1986.

TABLE I. - MEASURED CYCLIC TEETER ANGLES IN DEGREES FOR THE MOD-0 ONE-BLADED ROTOR

Yaw angle, deg	Alternator power, kW							
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
45 to 35	1.0	1.1	1.4	1.5	1.5	1.4		
35 to 25	.9	.9	1.1	1.0	.9	1.0		
25 to 15	.8	1.0	.8	.9	1.0	1.2		
15 to 5		.7	.8	.7	.8	.9	0.9	0.9
5 to -5	.3	.5	.7	.9	.6	.6	.6	.8
-5 to -15	.4	.7	.7	.6	.6	.4	.5	
-15 to -25	.5	.6	.6	.5	.5	.5	.4	
-25 to -35	.6	.7	.5	.6	.5	.6		
-35 to -45	.6	.6	.6					

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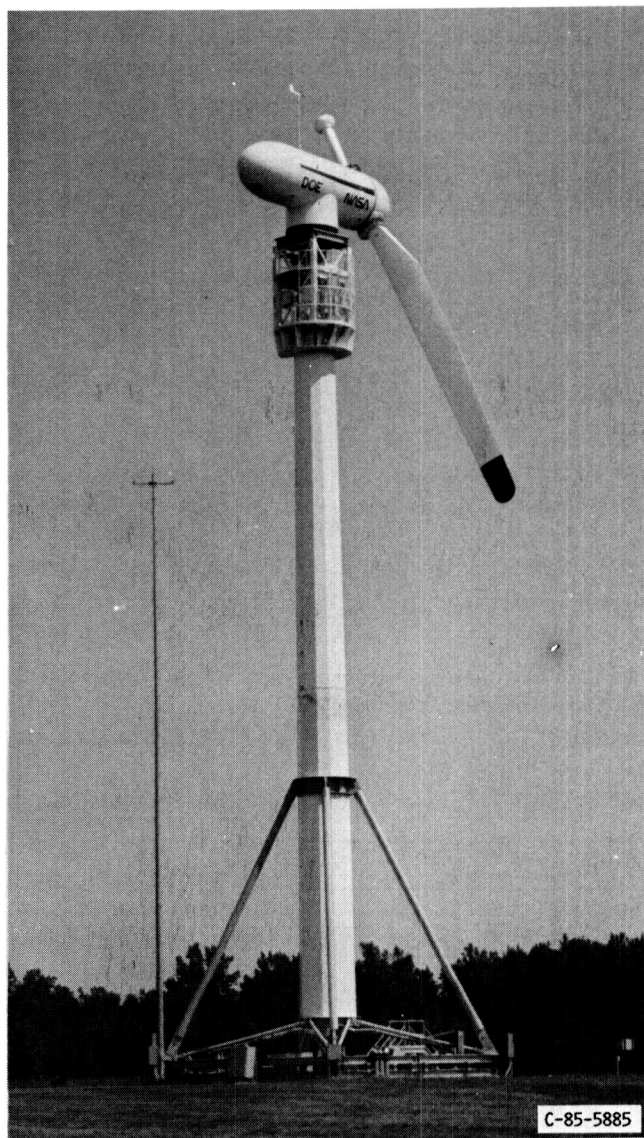


FIGURE 1. - MOD-0 WIND TURBINE WITH ONE-BLADED ROTOR.

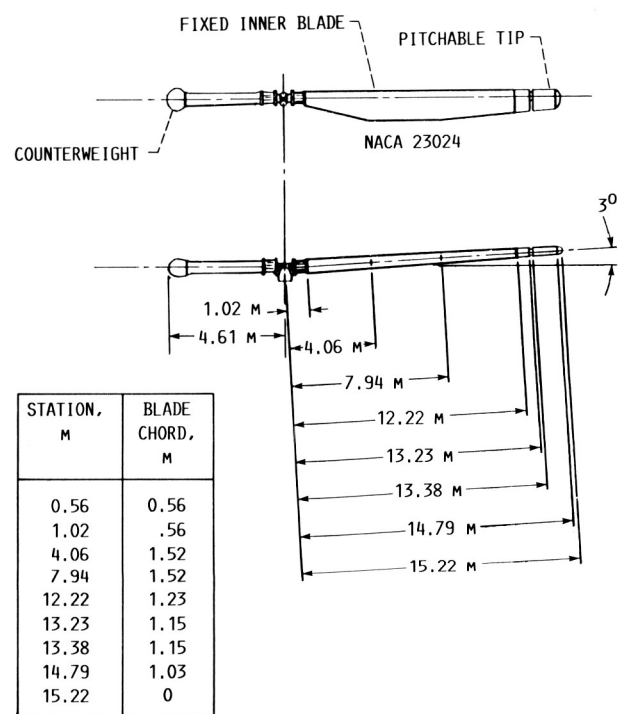


FIGURE 2. - MOD-0 ONE-BLADED ROTOR CONFIGURATION.

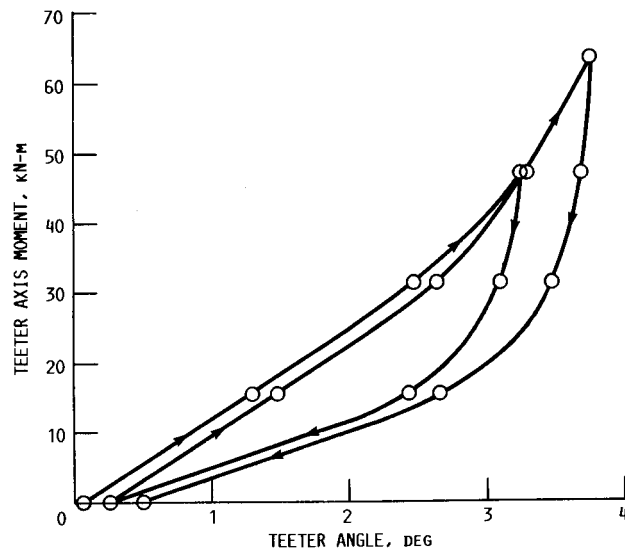


FIGURE 3. - TEETER AXIS MOMENT VERSUS TEETER ANGLE FOR THE MOD-0 ONE-BLADED ROTOR.

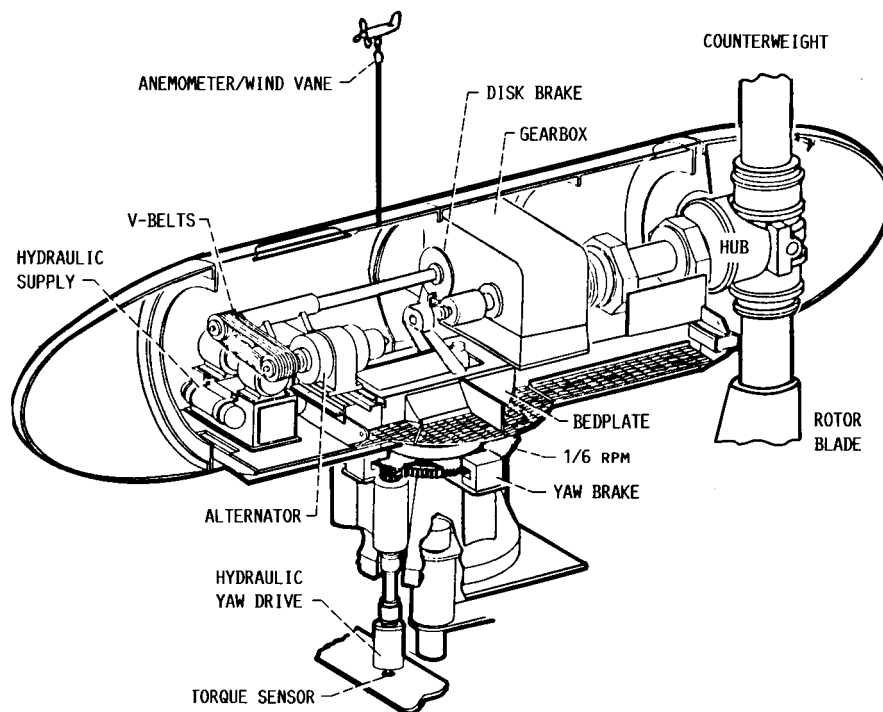


FIGURE 4. - MOD-0 WIND TURBINE NACELLE INTERIOR WITH A TEETERED HUB.

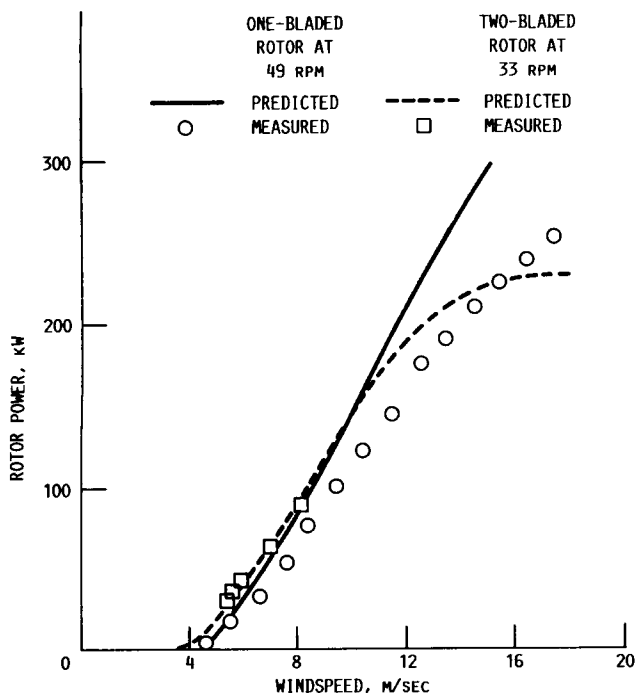


FIGURE 5. - MOD-0 WIND TURBINE PERFORMANCE.

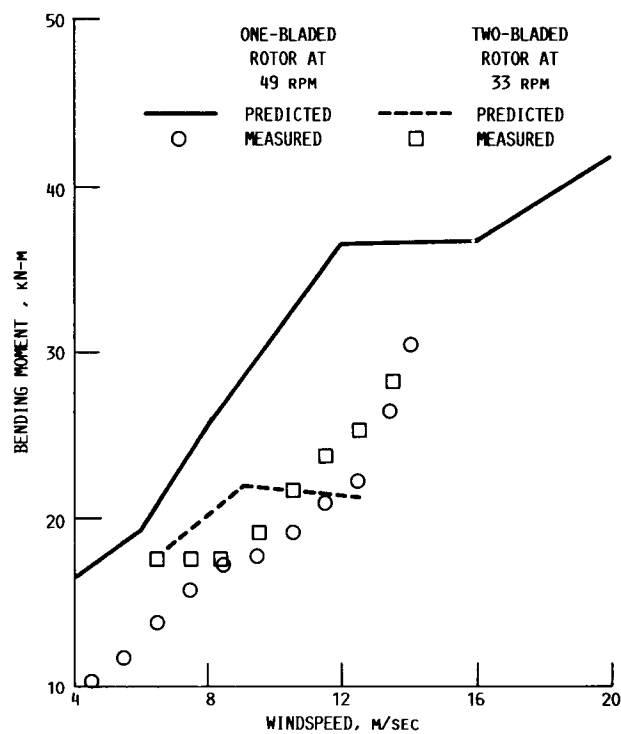


FIGURE 6. - CYCLIC FLATWISE BLADE-BENDING MOMENTS AT 5.3 PERCENT SPAN.

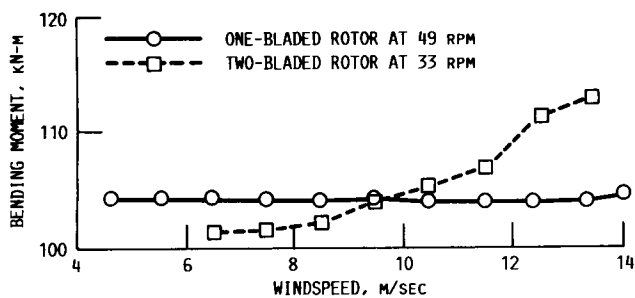


FIGURE 7. - MEASURED CYCLIC CHORDWISE BLADE-BENDING MOMENTS AT 5.3 PERCENT SPAN.

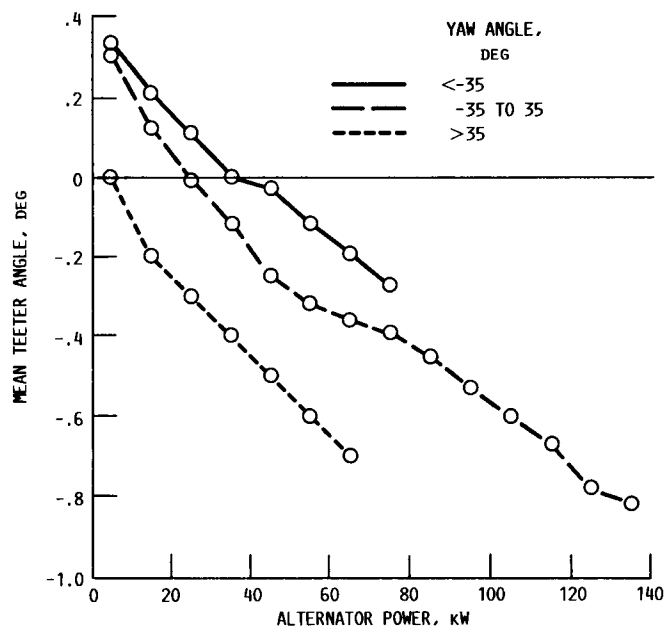


FIGURE 8. - MEASURED MEAN TEETER ANGLES FOR THE MOD-0 ONE-BLADED ROTOR.



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16. Abstract Tests were conducted on the DOE/NASA Mod-0 200-kW horizontal-axis wind turbine in a one-bladed rotor configuration. The objectives of the test were to evaluate the performance, loads, and dynamic characteristics of a one-bladed rotor, and then to compare these parameters with those of an aerodynamically similar two-bladed rotor configuration. Test operations showed that this intermediate-size (15.2-m radius) one-bladed rotor configuration can be operated successfully. The test results indicate that the one-bladed rotor had cyclic blade loads that were comparable to the loads of a two-bladed rotor. A moderate power penalty equivalent to a reduction in windspeed of 1 m/sec occurred with the one-bladed rotor when operated at a rotor speed 50 percent higher than that of the two-bladed rotor.					
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